

EPCOS 2015

Phase Change Materials in Light Modulating Applications Beyond Data Storage

Peiman Hosseini^{1,§}, Carlos Ríos^{1,§}, C David Wright² and Harish Bhaskaran^{1,*}¹ Department of Materials, University of Oxford, Oxford OX1 3PH United Kingdom² Department of Engineering, University of Exeter, Exeter EX4 4QF, United Kingdom[*harish.bhaskaran@materials.ox.ac.uk](mailto:harish.bhaskaran@materials.ox.ac.uk)[§] These authors contributed equally.

ABSTRACT

The use of phase change materials in applications that manipulate light reflectivity and transmissivity would appear to be both obvious and completely infeasible at the same time. It is obvious simply because many of these materials were developed with the primary aim of being able to store optically accessible data, which relied on the optical refractive index contrast between the two reversibly accessible solid states of the material. It would appear infeasible upon further consideration because, not only is the change in the refractive index not very large in the visible wavelengths, but also because the absorption of the material in both states resembles a metallic element as opposed to a dielectric, which would greatly reduce contrast. Over the last two and a half years, we have combined thin film optics concepts with phase change materials to essentially enable the use of such materials in light modulation applications such as displays, smart glazing and security markings. In this abstract, we also show some additional work done on two types of phase change materials, demonstrating that new areas of technological development for phase change materials are perhaps in some ways even more exciting than existing ones.

Key words: phase change materials, thin film optics, displays, smart glazing

1. INTRODUCTION

Re-writable optical storage discs utilize the remarkable and reversible optical refractive index of chalcogenide based phase change materials. This change in refractive index allows the storage of data¹ and intriguingly has led recently to an emerging application in integrated photonic waveguides and circuits²⁻⁴, something that will be presented at EPCOS 2015 by our collaborators from Karlsruhe.

All of these applications exploit the difference in the refractive index between the amorphous and crystalline phases of phase change materials. A key question is, from an applications standpoint, how can we exploit the fact that such materials are active both electrically and optically? After all, the last decade has seen a huge rise, including at this very event, in a range of electronic memory applications of phase change materials (PCMs)^{5,6} and even advanced non von Neumann computing paradigms using such materials⁷⁻¹⁰. We showed last year that indeed by incorporating such materials between transparent electrodes, ultra-high resolution displays can be created¹¹, opening up a completely new area of research in phase change optoelectronics.

A key challenge in designing such high resolution displays is to improve optical contrast in the region of wavelengths of interest. This can be achieved in conjunction with an appropriate design of the thin film stack, which ultimately determines the performance of an optical thin film system, especially in the reflective mode. One advantage of a multilayer stack utilizing PCMs is that this optical contrast increases exponentially for ultra-thin (< 10 nm) PCM layers¹¹. This counterintuitive property has been shown through very simple optical transfer simulation techniques¹², and recently sparked renewed interest when thin metallic (i.e. absorptive) films were shown also to display these properties^{13,14}. Extending this contrast enhancement to refractive-index-tunable and absorptive thin films, and confirming such enhancement experimentally would have important implications for the design of future solid state nanodisplays and optical storage systems^{11,15,16}, where a reduced volume of active phase change material

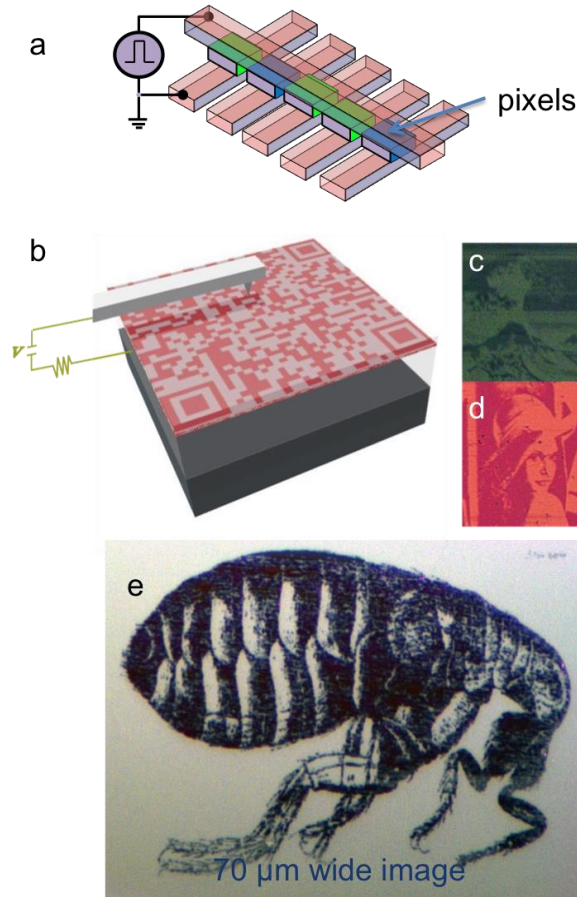


Figure 1 **a** Schematic of cross-bar pixels as a possible configuration for display applications of phase change materials; **b** schematic showing how an AFM tip can raster scan and 'write' areas of different contrast, in effect mimicking a display; **c** a 70 micron x 70 micron image reproduced at ultra-high resolution; **d** another image with a different colour set of 'Lena' reproduced, and **e** reproduction of Hooke's rendering of the flea in ultra-high resolution.

and later used in Solar cells^{12,19}, we can predict the colour changes in such films. We have shown optical changes in both reflective mode (such as for use on e-readers) as well as in transmissive mode (such as for use in smart glazing and colour filters)^{11,16}.

Samples consisted of planar films of phase change materials sandwiched between two transparent conductors (ITO in our case), with PCMs in as-deposited amorphous state. The phase change materials were switched locally by applying a voltage bias between an AFM cantilever and the ITO film under the PCM, as sketched in Figure 1b, which will in-effect mimic real pixels in future that can be developed using a cross-bar architecture as shown in the schematic in Figure 1a. Using the electrical conductivity of ITO, nanopixels can be written one-by-one by allowing current flow through the

would require considerably less energy to switch between phases^{17,18}. We have subsequently shown experimental results that confirm these simulations, even approaching an incredible contrast ratio of 6000%.

In this paper we present results of our ongoing work in this area to commercialize these novel applications of phase change materials. Here we present some results on both $\text{Ge}_2\text{Sb}_5\text{Te}_5$ (GST) and $\text{Ag}_3\text{In}_4\text{Sb}_{76}\text{Te}_{17}$ (AIST) using thin films of phase change materials sandwiched between two conducting electrodes.

2. EXPERIMENTS

For all our experiments, we decided to employ an AFM to showcase the feasibility of the concept. A key aspect was to show that electrically induced changes of phase can result in optical change of contrast so high that it can be visible. Another aspect was to show that by using simple modelling techniques originally developed by Heavens

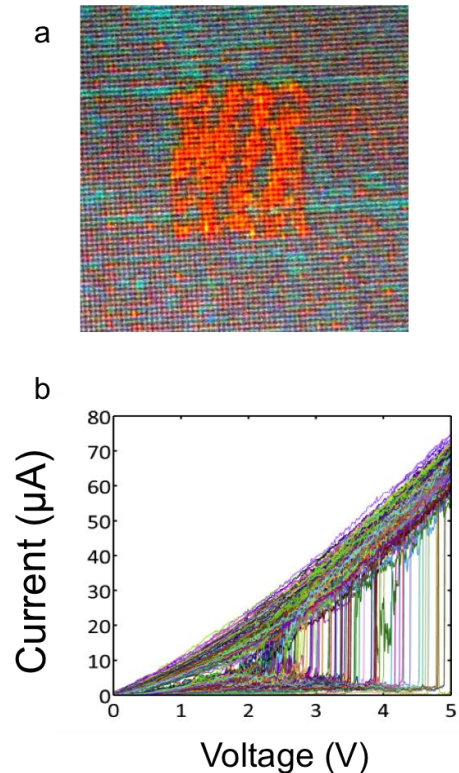


Figure 2. **a.** Image produced by individual IV curves on nanopillar structures as opposed to continuously scanned areas and **b.** reproduction of all the IV curves used to produce the image which shows a huge concentration of threshold voltages between 2.2 - 2.8 V

PCM which switches it to crystalline state. This can be done by locally switching point by point or by modulating the voltage while scanning the surface back and forth at a fixed frequency. Using scanning mode and setting 0V to black and 6V to white, we were able to write $70 \times 70 \mu\text{m}$ binary images onto the PCM layer as shown in Figure 1c-e. These images present an outstanding resolution with features below 100 nm. In order to verify that scanning alone does not result in a visible change, we also carried out experiments whereby we switch individual pixels by doing independent IV's on the surface. Even under this condition a clear visible pattern emerged. This is shown in Figure 2a. Figure 2b demonstrates that given the extremely large numbers of IVs and the very unclean surface of the ITO, the vast majority of the threshold voltages are still well within a tight bound, which will allow for easy integration into drive electronics into the future.

Furthermore, we calculated the wavelength at spectra peak maximum as function of phase state, ITO and PCM thickness, as presented in Figure 3a for AIST and Figure 3b for GST. From these figures, it is clearly evident that there is considerable similarity between both materials as they present a very similar

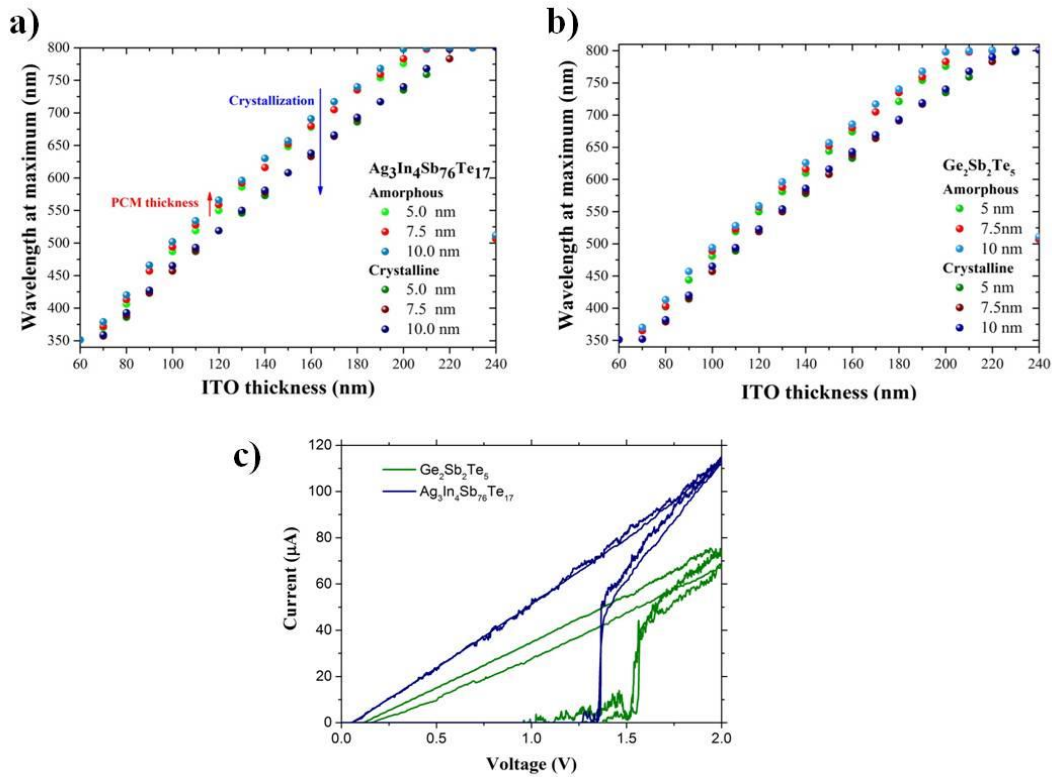


Figure 3. Colour variation (wavelength at maximum of reflectance spectrum) as function of ITO and PCM thickness for **a.** AIST and **b.** GST. **c.** Comparison between GST and AIST I-V curves measured on uniform film devices.

behaviour in response to variation in the parameters of the thin film stack. Reflectance peaks centered in any colour in the visible spectrum are achievable for both materials by changing only the ITO spacer dimensions. Moreover, the same device leads to similar colour when using both phase-change alloys given the similarity between the refractive indexes^{4,20,21}, despite the different nature of their nucleation and growth processes. The effect of the thickness of the PCMs lies only in a slight red-shift as it gets thicker, in both cases. However, the blue-shift resulting from the high to low 'real' refractive index and low to high extinction coefficient transition, when switching from amorphous to crystalline state, is definitely more pronounced. This is the reason why colour switching is possible. Considering the shift between spectra in amorphous and crystalline, only for ITO thicknesses in the range 100-160 nm AIST presents, in average, a modest peak shift of 6 nm larger than for GST.

Next, we measured the characteristic IV curves of both GST and AIST uniform films in a configuration 10nm ITO/ 7nm PCM/ 70nm ITO / Mirror. Results are depicted in Fig. 3c, where electrical switching towards a less resistive state, i.e. the crystalline phase, is clearly observed. From this figure, we also obtain the threshold voltage for both materials, being equal to 1.40 ± 0.15 V for AIST and 1.50 ± 0.15 V for GST. Moreover, AIST presents a less resistive state with 14.3 ± 1.0 k Ω while for GST we observed 28.6 ± 1.5 k Ω . However, it is important to take into account the resistance of the tip and ITO top layer and the possible impurities sitting on the tip. Therefore, even though results for GST suggest a larger threshold voltage, it is not considerably higher than for AIST; from the practical point of view in terms of display applications, both devices behave almost identically.

3. RESULTS & DISCUSSION

As already discussed in the experimental section above, we have shown that two phase change materials, commonly employed in optical data storage can be used to create prototype ultra-high resolution displays. It is noted that the creation of optical contrast at a certain wavelength can be kept independent of the thickness of the phase change material itself. This is a key aspect of this design; essentially this ensures that the switching ‘threshold’ voltage can always be kept constant, whereas pixels of various colours can be created by varying the thickness of the lower electrode. This allows for modular design of pixels without affecting the threshold characteristics of individual pixels, in effect allowing for a simpler design of the “switching” electronics.

4. CONCLUSION

In conclusion, we have shown that solid state materials can be used as display elements and still create astoundingly high contrast reflective displays that are also non-volatile. Given the high speed switching capabilities of phase change materials, the future is very bright, especially as the ultra-high resolution and high speeds are crucial for future micro-displays and holographic displays. Thus these materials may present a rather unique value proposition in an area where other materials and devices can find it hard to compete. Given that phase change materials are inorganic, have proven lifetimes and switching cycles far exceeding requirements for display applications and require little or no materials development, they might actually herald an unexpected, but welcome change in these areas.

REFERENCES

- 1 M. Wuttig, N. Yamada, *Nat. Mater.* **6** (2007), 824.
- 2 C. Rios, P. Hosseini, C. D. Wright, H. Bhaskaran, W. H. P. Pernice, *Adv. Mater.* **26** (2013), 1372.
- 3 M. Rudé, J. Pello, R. E. Simpson, J. Osmond, G. Roelkens, J. J. G. M. van der Tol, V. Pruneri, *Appl. Phys. Lett.* **103** (2013), 141119.
- 4 W. H. P. Pernice, H. Bhaskaran, *Appl. Phys. Lett.* **101** (2012), 171101.
- 5 S. Raoux, G. W. Burr, M. J. Breitwisch, C. T. Rettner, R. M. Shelby, M. Salinga, D. Krebs, C. H. Lam, *I. Sb.* **52** (2008), 465.
- 6 A. Pantazi, A. Sebastian, N. Papandreou, M. J. Breitwisch, C. Lam, H. Pozidis, E. Eleftheriou, **n.d.**, 34.
- 7 C. D. Wright, Y. Liu, K. I. Kohary, M. M. Aziz, R. J. Hicken, *Adv. Mater.* **23** (2011), 3408.
- 8 C. D. Wright, P. Hosseini, J. a. V. Diosdado, *Adv. Funct. Mater.* **23** (2013), 2248.
- 9 M. Suri, O. Bichler, D. Querlioz, O. Cueto, L. Perniola, V. Sousa, D. Vuillaume, C. Gamrat, B. DeSalvo, 2011 *Int. Electron Devices Meet.*(2011), 4.4.1.
- 10 P. Hosseini, A. Sebastian, N. Papandreou, D. Wright, H. Bhaskaran, *Electron Device Lett. IEEE*(2015), DOI 10.1109/LED.2015.2457243.
- 11 P. Hosseini, C. D. Wright, H. Bhaskaran, *Nature* **511** (2014), 206.
- 12 O. Heavens, *Optical Properties of Thin Solid Films*, Dover Publications, Inc., New York, USA, (1991).
- 13 M. a. Kats, D. Sharma, J. Lin, P. Genevet, R. Blanchard, Z. Yang, M. M. Qazilbash, D. N. Basov, S. Ramanathan, F. Capasso, *Appl. Phys. Lett.* **101** (2012), 221101.

- 14 M. a. Kats, F. Capasso, *Appl. Phys. Lett.* **105** (2014), 131108.
- 15 F. F. Schlich, P. Zalden, A. M. Lindenberg, R. Spolenak, *ACS Photonics* **2** (2015), 178.
- 16 P. Hosseini, H. Bhaskaran, *Proc. SPIE* **9520** (2015), 95200M.
- 17 B.-S. Lee, R. M. Shelby, S. Raoux, C. T. Retter, G. W. Burr, S. N. Bogle, K. Darmawikarta, S. G. Bishop, J. R. Abelson, *J. Appl. Phys.* **115** (2014), 063506.
- 18 F. Xiong, A. D. Liao, D. Estrada, E. Pop, *Science* (80-.). **332** (2011), 2.
- 19 G. F. Burkhard, E. T. Hoke, M. D. McGehee, *Adv. Mater.* **22** (2010), 3293.
- 20 Z. Guang-Jun, G. Dong-Hong, G. Fu-Xi, *Chinese Phys.* **14** (2005), 0218.
- 21 S. Y. Kim, S. J. Kim, H. Seo, M. R. Kim, *Proc. SPIE* **3401** (1998), 112.